UDC 621.396.673
621.372.622

BBC

RESEARCH DEPARTMENT REPORT

The design of combining circuits for medium-frequency transmitters working into a common aerial

No. 1969/6

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

THE DESIGN OF COMBINING CIRCUITS FOR MEDIUM-FREQUENCY TRANSMITTERS WORKING INTO A COMMON AERIAL

Research Department Report No. 1969/6
UDC 621.396.673
621.372.622

It uses SI units in accordance with B.S. document PD 5686.

R.D.C. Thoday, M.I.E.R.E.
P. Knight, B.A., M.I.E.E.

D. Maurice

Head of Research Department

(RA-34)

Research Department Report No. 1969/6

THE DESIGN OF COMBINING CIRCUITS FOR MEDIUM-FREQUENCY TRANSMITTERS WORKING INTO A COMMON AERIAL

(RA-34)

April 1969

Research Department Report No. 1969/6
UDC 621.396.673
621.372.622

THE DESIGN OF COMBINING CIRCUITS FOR MEDIUM-FREQUENCY TRANSMITTERS WORKING INTO A COMMON AERIAL

SUMMARY

Two or more m.f. transmitters separated in frequency by as little as 3% may be operated into a common aerial provided its impedance is first transformed to a fairly high resistance. Rejector circuits are used to isolate the transmitters from each other and prevent excessive cross-modulation and intermodulation occurring in their output stages. A satisfactory performance can be obtained using rejector circuits with normal components, but the maximum powers which can be fed to a common aerial may be limited by the voltage ratings of the capacitors in the combining circuit.

1. INTRODUCTION

It is common practice at low-power m.f. transmitting stations for up to four transmitters to feed a single aerial. While this presents no difficulty when the individual frequency separations exceed 10%, complications may arise if the separations are smaller. This report describes the design and performance of combining circuits for frequency separations of less than 10%. Separations less than about 20 kHz (2% at 1 MHz) are not likely to be used, however, because of limitations imposed by receiver selectivity.[1]

When two transmitters are combined into a common aerial, an arrangement similar to that shown in Fig. 1 is usually adopted. If more than two transmitters are connected to the point A, additional rejector circuits have to be inserted in the feeders from the transmitters but the principle remains the same. The rejector circuits ensure that the greater part of the transmitter power reaches the aerial and they also prevent excessive cross-modulation and intermodulation* occurring in the output stages of the transmitters. In the design of the rejector circuits the suppression of the modulation products is the overriding consideration. Although cross-modulation and intermodulation levels are difficult to calculate, experience has shown that acceptable levels result if the unwanted voltage which reaches the anode of the output valve of a transmitter is less than 10 volts r.m.s. when the e.h.t. supply to the valve is removed. Rejector circuits are therefore designed with this criterion in mind.

Frequency separations as low as 3% are now being considered and calculations have shown that very-high-Q rejector circuits are required for certain aerial impedances if the criterion stated above is to be satisfied. The difficulty of using high-Q circuits can be overcome by inserting an additional matching network between the point A of Fig. 1 and the aerial, to transform the aerial impedance to one which is considerably greater than the transmitter load impedance and predominantly resistive. The majority of low-power transmitters are designed for load impedances between 50 and 80 ohms and calculations have shown that practicable rejectors can be used if the impedance at A is approximately equal to 500 + j0 ohms. If this impedance is made exactly 500 ohms midway between the two frequencies, it will be sufficiently close to 500

* Cross-modulation is the transfer of modulation from one carrier frequency to another. Intermodulation is the generation of spurious frequencies such as the sum and difference of two carrier frequencies.

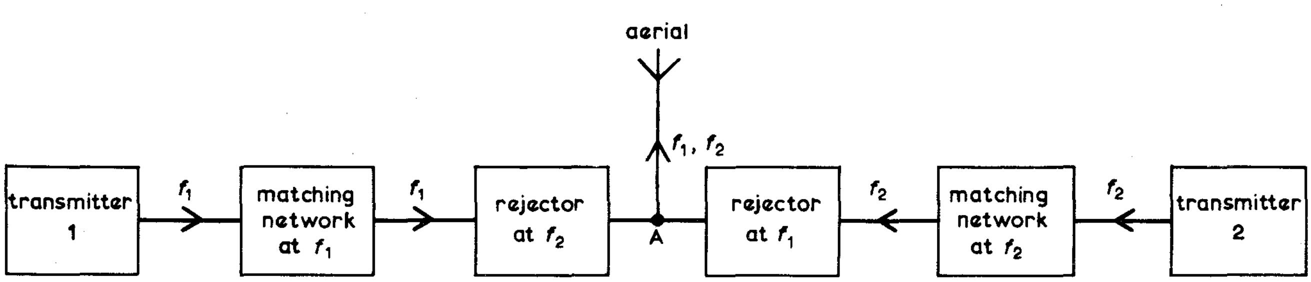

Fig. 1 - General arrangement of networks

ohms at both f_1 and f_2 for the performance of rejector circuits designed for 500 ohms to be almost unaffected. The matching circuits in the transmitter branches are designed to transform the true impedance at A, seen through the rejector circuit, to the load impedance required by the transmitter (usually 80 ohms).

This arrangement is shown in more detail in Fig. 2. It is assumed that the two transmitters and the point A are close together, i.e. in the same building. If the aerial is less than $0{\cdot}1\lambda$ from the transmitters (where λ is the wavelength) the primary matching circuit may be situated either in the transmitter building or below the aerial. If the aerial is more than $0{\cdot}1\lambda$ from the transmitters, the aerial should be matched to the feeder and the impedance transformed to 500 ohms in the transmitter building. Whatever arrangement is adopted, care should be taken to ensure that the impedance at A is as close to 500 ohms as possible at both f_1 and f_2.

The detailed design of the combining circuit is considered in the sections which follow and an example of the design procedure is given in Appendix II.

2. THE DESIGN OF THE REJECTOR CIRCUITS

Each rejector circuit must satisfy the following requirements:

(i) the impedance at the rejection frequency must be high enough to prevent the unwanted r.m.s. voltage at the valve anode exceeding 10

(ii) the rejector circuit must not introduce excessive loss at the pass frequency

(iii) the Q must not be too high or the rejection at the sideband frequencies will be poor and the tuning of the circuit will be critical.

The design of circuits which satisfy these requirements will now be discussed.

2.1. Impedance at the Rejection Frequency

When the f_1 transmitter radiates, a small fraction of the voltage at A (Fig. 2) appears at the anode of the output stage of the f_2 transmitter. This fraction depends partly on the impedance of the f_1 rejector (a pure resistance R_D at f_1) and partly on the design of the output circuit of the transmitter. With low-power transmitters, π-networks are commonly used in place of conventional tank circuits and coupling coils. The equivalent circuit of the f_2 transmitter branch therefore takes the form shown in Fig. 3 at f_1; a similar circuit may be drawn for the f_1 transmitter branch at f_2.

Anode voltages have been computed for a range of values of R_D for frequency separations between 2 and 10%. In every case, the matching circuit components were assumed to be adjusted so as to present the idle transmitter with a resistive impedance of 80 ohms at its working frequency. Values of R_D which give exactly 10 volts at the anode of one transmitter as a result of the other transmitter radiating 1 kW were then found by interpolation and are shown in Fig. 4. Values of R_D for other powers may be obtained by multiplying by $\sqrt{P}$, where P is the power of the rejected transmitter in kW.

In general, the component values of the output circuit of a transmitter are chosen to give efficient power transfer into the load, without considering requirements for rejection of power from other transmitters; Fig. 4 therefore shows curves for three values of output-circuit loaded Q (Q_L). In practice X_1 has a fixed value and X_2 and X_3 are adjusted for maximum power transfer; Q_L may then be calculated from the measured values of X_2 and X_3.* For the computations, X_1 was specified as -160 ohms, since further computations indicated that very high values of R_D might be required if $|X_1|$ was less than 80 ohms. Although Fig. 4 was calculated for a load impedance of 80 ohms it may be applied with little error to a load of $80n$ ohms (where n is a scaling factor) provided X_1 is made equal to $-160n$ ohms and the value of R_D obtained from curves is also multiplied by n. The Q of the rejector circuit was assumed to be 400 but Fig. 4 is reasonably accurate for Q values between 200 and 800. The actual choice of Q value is governed by factors discussed in the next section.

2.2. Circuit Magnification Factor (Q)

The Q of the rejector circuit must exceed a minimum value or the loss at the pass frequency will be excessive. In this report the maximum permissible pass loss is taken to be 0·5 dB, i.e. 11% of transmitter power is lost in the rejector.

The pass loss L is given by

$$L = 10 \log_{10}(1 + R_S/R_A) \text{ dB} \qquad (1)$$

where R_A is the series resistance of the load at A in Fig. 2 (nominally 500 ohms) and R_S is the resistive part of the rejector impedance at the pass frequency. For losses under 1 dB, L may be expressed in the form

$$L = 4{\cdot}34 \log(1 + R_S/R_A) \simeq 4{\cdot}34\, R_S/R_A \text{ dB} \qquad (2)$$

In Appendix I it is shown that, for frequencies more than 2% but less than 10% from the resonant frequency, R_S is given approximately by

$$R_S \simeq R_D/(2Q\nu)^2 \qquad (3)$$

* If the load presented to the transmitter is 80 ohms and $X_1 = -160$ ohms, the values of X_2 and X_3 are $64Q_L$ and $-64\,(Q_L - 0{\cdot}25)$ ohms respectively.

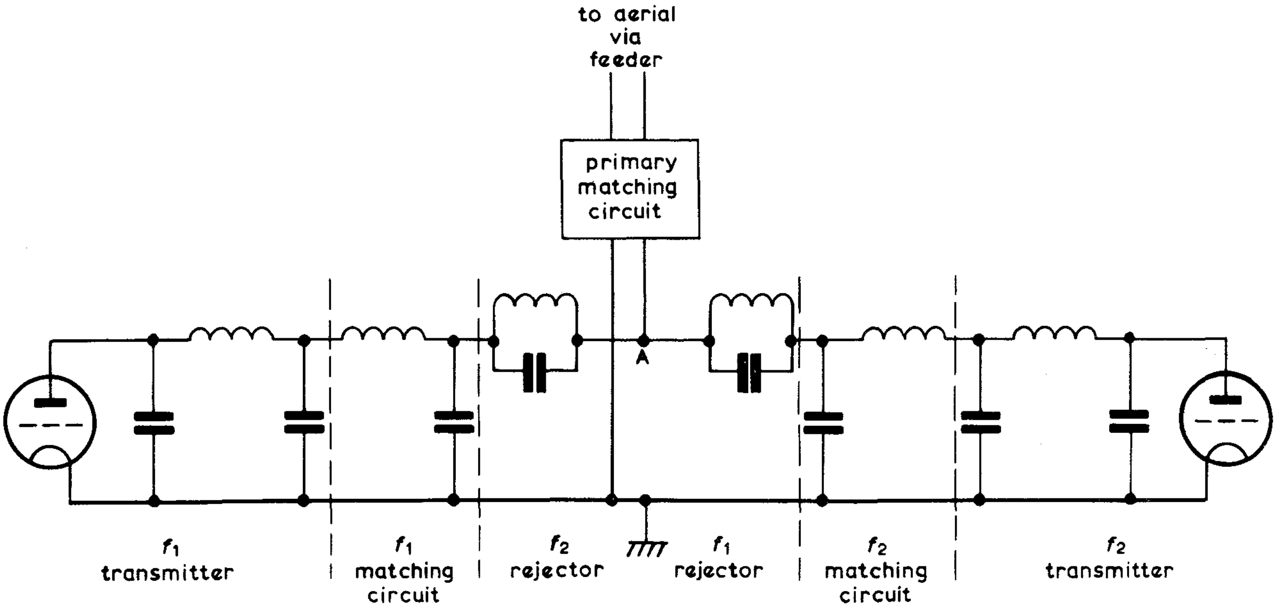

Fig. 2 - Combining network for two transmitters separated in frequency by less than 10%

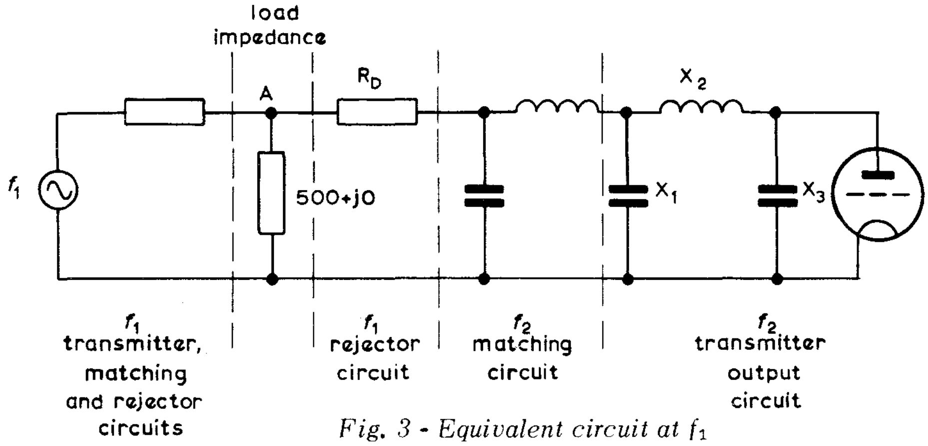

Fig. 3 - Equivalent circuit at f_1

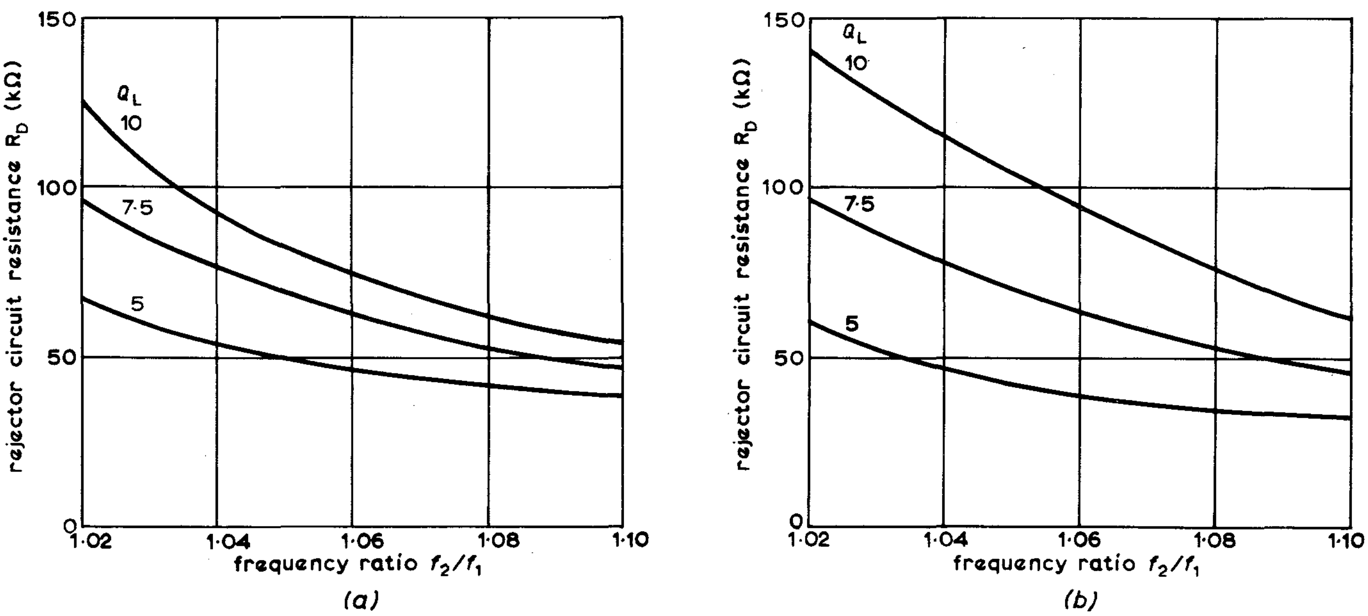

Fig. 4 - Values of rejector circuit resistance which give 10 volts r.m.s. at the valve anodes

(*a*) Rejector circuit in the f_1 transmitter branch (*b*) Rejector circuit in the f_2 transmitter branch

Q_L is the loaded Q of the output circuit of the idle transmitter

Power of rejected transmitter, 1 kW

where $\nu = (f-f_0)/f_0$ is the fractional deviation from the resonant frequency f_0. The pass loss is therefore given approximately by

$$L \simeq \frac{1{\cdot}08R_D}{(Q\nu)^2 R_A} \text{ dB} \tag{4}$$

From this it follows that the loss will be less than 0·5 dB provided

$$Q > \frac{(2R_D/R_A)^{1/2}}{\nu} \tag{5}$$

Equation (5) specifies the lower limit for Q. For example, if $\nu = 0{\cdot}04$ (4%), $R_D = 100{,}000$ ohms and $R_A = 500$ ohms, then Q must exceed 500.

Although a higher value of Q will give a lower pass loss, it may lead to inadequate rejection of sideband frequencies. A reasonable criterion to adopt is that the rejection should be within 6 dB of that at the carrier over a bandwidth of ± 1 kHz, since most of the power in an amplitude-modulated wave is contained within this band. Poorer rejection may, however, be tolerated outside the band.

The cause of poor rejection at sideband frequencies with high-Q circuits is the rapid reduction of the rejector circuit impedance which occurs away from resonance. Equation (8) of Appendix I shows that the modulus of the impedance falls to $0{\cdot}7R_D$ when $\nu = \pm 1/2Q$; the unwanted voltage at the transmitter would then be expected to be 3 dB greater than that at the carrier frequency. There is, however, a possibility that the series reactance of the rejector circuit may resonate with the matching circuit, in which case the unwanted voltage would be 6 dB greater than at the carrier frequency. Thus if $\nu = \pm 1/2Q$ is made to correspond to ± 1 kHz, the 6 dB criterion is bound to be satisfied at all frequencies within 1 kHz of the carrier. Now for ± 1 kHz, $\nu = \pm 1/f_0$, where f_0 is the carrier frequency in kHz. It follows therefore that the criterion is satisfied if Q is less than $f_0/2$. Thus the highest Q value which will be required in the m.f. band (at 1·6 MHz) is 800 and this can be achieved with normal components. At the low-frequency end of the band (0·530 MHz) Q should not exceed 265 for adequate sideband rejection. This value may, however, conflict with the minimum Q required for low pass loss and a compromise may be necessary; the use of the Q value which gives exactly 0·5 dB pass loss is then recommended. A compromise is unlikely to be required above 1 MHz, assuming a transmitter frequency difference of not less than 3%.

To summarize, the Q of the rejector circuit should, if possible, lie within the range

$$\frac{(2R_D/R_A)^{1/2}}{\nu} < Q < \frac{f_0}{2} \tag{6}$$

However, if the Q of an available coil is r times greater than the value desired it may be used with advantage provided R_D is increased to r^2R_D. The rejection at both carrier and sideband frequencies will then be improved and the pass loss will be unchanged. If R_D were not increased the pass loss would be reduced but the rejection at the sidebands would be degraded.

2.3. Component Values and Ratings

Having determined the values of R_D and Q which give the required performance, the rejector circuit reactances (X_L and X_C) are calculated from the relationship $X_L = -X_C = R_D/Q$. If a variable capacitor cannot be used, a fixed capacitor whose reactance is greater, rather than less, than R_D/Q should be chosen, since this ensures that the specified anode voltage is not exceeded. In general, tapped rejector circuits do not offer any advantage.

Circulating currents flow in the rejector circuit at both the rejection and pass frequencies. The maximum voltage across the capacitor is the arithmetic sum of the voltages at the two frequencies, since these will periodically add in phase.

At the rejection frequency f_1, the voltage V_1 across the capacitor is essentially the same as that across the load and is therefore equal to $(P_1R_1)^{1/2}$, where P_1 is the power the f_1 transmitter delivers to the load and R_1 is the parallel resistance of the load at f_1. At the pass frequency f_2 the impedance of the rejector is predominantly reactive and equal to $\pm jR_D/2Q\nu$. Thus the voltage at f_2 across the capacitor is

$$V_2 = \frac{R_D}{2Q\nu}\left(\frac{P_2}{R_{A2}}\right)^{1/2} \tag{7}$$

where P_2 is the power delivered by the f_2 transmitter to the load and R_{A2} is the series resistance of the load at f_2. The total peak voltage when both transmitters are modulated 100% is $2{\cdot}82(V_1 + V_2)$. If the frequency separation is small the peak voltage will be large even for moderate powers; in the example given in Appendix II it is of the order of 10 kV for two 1 kW transmitters separated by 3·4%.

3. THE DESIGN OF THE MATCHING CIRCUITS

The impedance of the rejector circuit at the pass frequency is given approximately by Equation (9) in Appendix I. This impedance must be added to the series impedance of the load and transformed to a resistive value (usually 80 ohms) with a simple matching network.

If f_1 is less than f_2, the f_1 rejector will look like a capacitance at f_2. The impedance presented to the f_2 transmitter is then most conveniently matched by

means of a shunt capacitance and series inductance, as shown in the right-hand arm of Fig. 2. Conversely the most convenient matching network for the f_1 transmitter would be a shunt inductance and a series capacitance. Calculations have shown, however, that the use of the latter network may lead to a resonance condition in the f_1 transmitter at the unwanted frequency f_2; the alternative network (shunt capacitance and series inductance) is therefore used instead.

The voltage across the matching circuit capacitor is comparable with that across the rejector circuit because of the high reactance of the latter at the pass frequency. If the impedance to be matched is Z, the voltage across the capacitor is given by $|Z|(P/R)^{1/2}$, where P is the transmitter power and R is the real part of Z. The voltage due to the rejected transmitter is very small and may be neglected.

4. COMBINING CIRCUITS FOR MORE THAN TWO TRANSMITTERS

The principles described may be extended to three or more transmitters feeding a common aerial, the exact arrangement depending mainly on their frequency separations. Thus three transmissions separated in frequency by more than 10% would be fed directly to the aerial, as shown in Fig. 5(*a*), and each transmitter branch would contain a matching circuit and two rejectors. If two closely-spaced transmitters are to be combined with one which is more widely spaced, an arrangement of the type shown in Fig. 5(*b*) would be used. Here the transmitter with the more widely spaced frequency (f_1) feeds the aerial directly via rejectors while the more closely spaced pair feed a nominal 500-ohm impedance derived from a primary

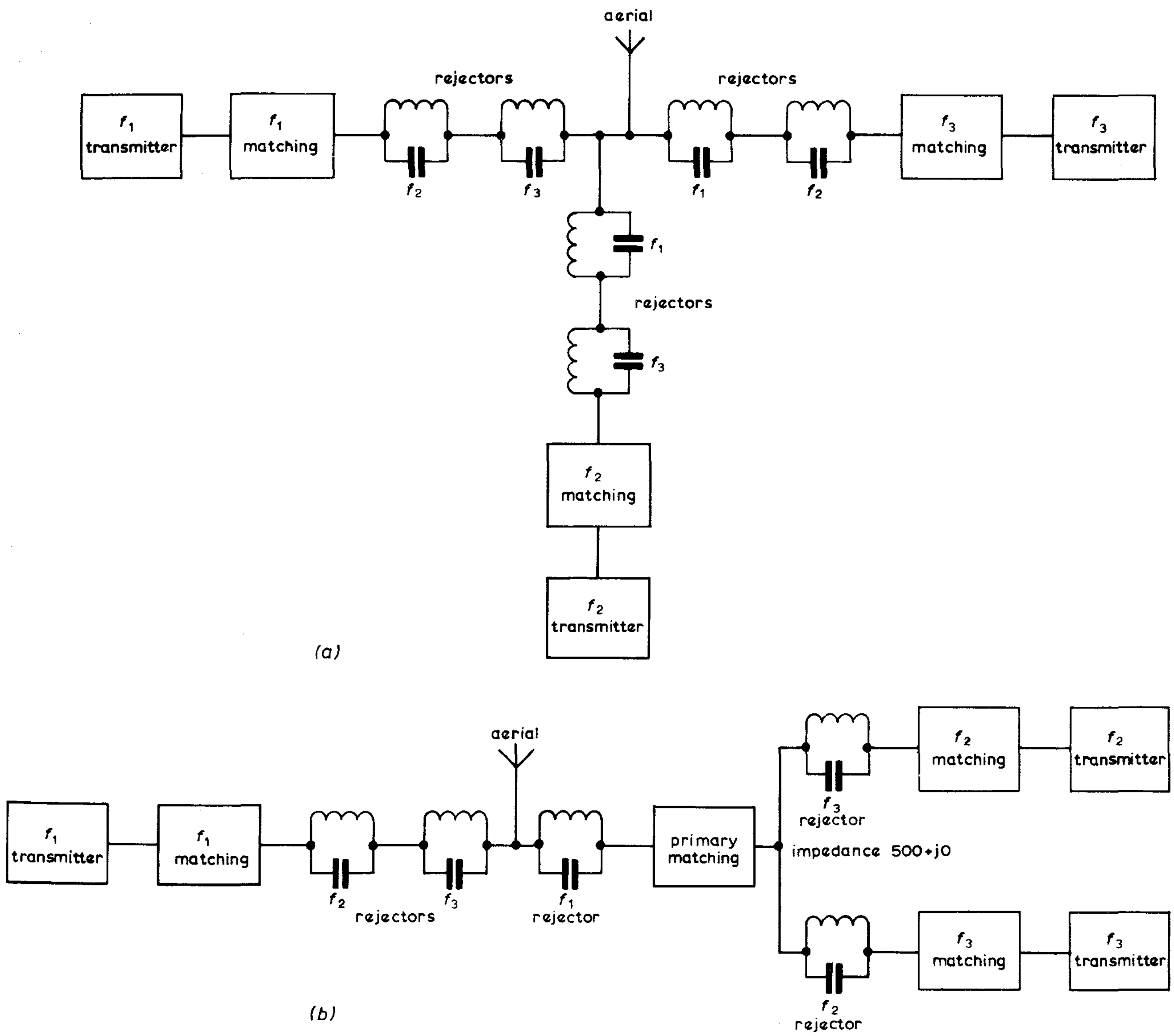

Fig. 5 - Three transmitters fed to a common aerial

(*a*) Three widely-spaced frequencies (*b*) One widely-spaced frequency (f_1) and two closely-spaced frequencies

matching circuit. Three transmitters with closely-spaced frequencies would be combined as in Fig. 5(*a*), but with the aerial impedance transformed to 500 ohms at the central frequency.

Whichever arrangement is adopted, the design of the rejector circuits follows the principles described in Section 2. Although two or more rejectors in series will have a higher pass loss than one rejector, some of the rejectors will inevitably be tuned to frequencies well away from the pass frequency and will have correspondingly lower losses. Thus the total pass loss in many cases may not be much greater than that occurring when only two transmitters are combined.

5. CONCLUSIONS

It has been shown theoretically that two m.f. transmissions separated in frequency by as little as 3% may be combined in a common aerial provided the latter is first matched to 500 ohms. The use of rejector circuits having a Q-factor less than 800 gives satisfactory suppression of cross-modulation and intermodulation products at both carrier and sideband frequencies, while the pass loss does not generally exceed 0·5 dB. The principles described can be extended to three or more transmitters operating into a common aerial.

With such small frequency separations, however, the peak voltages across the capacitors in the combining circuit may be quite large; for example with 1 kW transmitters they may be as much as 10 kV. Thus the voltage ratings of commercially-available capacitors may impose an upper limit on the powers of transmitters which can be combined in the manner described.

The principal applications for close frequency combining will probably be at low-power stations. Nevertheless the design principles set out in this report can be used for high-power stations although the peak voltages encountered may present a difficulty.

6. REFERENCE

1. CCIR Documents of the XIth Plenary Assembly, Oslo 1966, Rec. 499.

APPENDIX I

The Impedance of a Rejector Circuit

A simple rejector circuit consists of an inductance L in parallel, with a capacitance C, as shown in Fig. 6. Providing the circuit has a high Q value, losses may be represented by a parallel resistance $R_D = \omega_0 LQ$, where ω_0 is the angular frequency at which the circuit resonates. At resonance, $\omega_0^2 LC = 1$ and the reactances of the inductance and capacitance are equal and opposite. The impedance of the circuit is then equal to R_D.

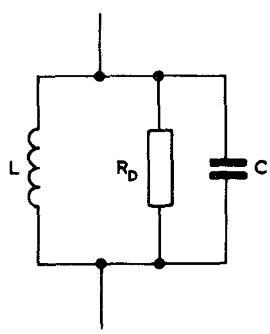

Fig. 6 - Equivalent circuit of a rejector

At an angular frequency ω, the admittance Y of the circuit is

$$Y = \frac{1}{R_D} + \mathrm{j}\left(\omega C - \frac{1}{\omega L}\right)$$

$$= \frac{1}{R_D} + \frac{\mathrm{j}C}{\omega}(\omega^2 - \omega_0^2)$$

If the deviation from the resonant frequency is less than 10%, $\omega_0 + \omega \simeq 2\omega$ and consequently

$$Y \simeq \frac{1}{R_D} + \mathrm{j}2\omega C\nu = \frac{1}{R_D}\left[1 + \mathrm{j}2Q\nu\right]$$

where $\nu = (f - f_0)/f_0$ is the fractional deviation from the resonant frequency. The impedance of the rejector is therefore

$$Z_S = R_S + \mathrm{j}X_S = \frac{R_D(1 - \mathrm{j}2Q\nu)}{1 + (2Q\nu)^2} \tag{8}$$

If $Q > 200$ and $\nu > 0{\cdot}01$ (1%)

$$Z_S \simeq \frac{R_D}{2Q\nu}\left[\frac{1}{2Q\nu} - \mathrm{j}\right] \tag{9}$$

since $(2Q\nu)^2 \gg 1$.

APPENDIX II

An Example Illustrating the Design of a Combining Circuit

An example is given of the design of a combining circuit for two 1 kW transmitters operating on 1052 and 1088 kHz. These two frequencies, used by the BBC, are separated by 3·4%.

The aerial will be assumed to be the standard type used at BBC low-power stations; this consists of a T suspended between two 38 m (126 ft) masts spaced 61 m (200 ft). Measured impedances of a typical aerial are given in Table 1.

TABLE 1

Aerial Impedance

Frequency kHz	Impedance (ohms)
1052	23·2 + j40
1070	24·2 + j50
1088	25·4 + j60

In designing the combining circuit, shown in Fig. 7, the aerial is first matched to 500 ohms at the mid-frequency, 1070 kHz. This requires a series inductance L_1 and a shunt capacitance C_1; their reactances at 1070 kHz are 57·2 and –113 ohms respectively. The impedance at A then has the values given in Table 2.

Fig. 4 shows that, if the transmitter output circuits have a loaded Q of 5, rejector circuit impedances of 60,000 ohms will be adequate for both transmitter branches. Equation (6) then shows that the rejector circuit Qs must lie within the range $455<Q<535$; a value of 500 will be chosen. The rejector circuit reactances, equal to $\pm R_D/Q$ are therefore ± 120 ohms at their resonant frequencies.*

* This would require rejector circuit capacitances of 1220 and 1260 $\mu\mu$F. In practice standard values of 1200 or 5 x 250 $\mu\mu$F could be used with negligible change in performance.

TABLE 2

Impedance at the point A, Fig. 7

Frequency (kHz)	Series Impedance (ohms)	Parallel Impedance (ohms)
1052	347 + j163	423 ‖ j900
1070	500 + j0	500 ‖ j∞
1088	451 – j236	575 ‖ –j1099

Note: ‖ signifies 'in parallel with'

The matching circuits in the transmitter branches are now designed. At 1052 kHz the impedance of the 1088 kHz rejector is 52 + j1765 ohms and the impedance at the point B (Fig. 7) is therefore 399 + j1930 ohms. This is matched to 80 ohms with a shunt reactance of –615 ohms and a series reactance of 879 ohms. At 1088 kHz the impedance of the 1052 kHz rejector is 52–j1765 ohms and the impedance at C is 503–j2000 ohms. This is matched to 80 ohms with a shunt reactance of –1350 ohms and a series reactance of 819 ohms.

This completes the design of the combining circuit apart from the calculation of the voltage ratings of the capacitors. Its performance may now be verified.

Pass Loss. The series resistance of both rejectors is 52 ohms at the pass frequency and the series resistance of the load is given in Table 2. Equation (1) gives the pass losses, which are 0·61 and 0·47 dB at 1052 and 1088 kHz respectively.

Unwanted Voltages at the Valve Anodes. The 1052 kHz transmitter delivers 870 watts to the load and the voltage at A is 608 volts. This voltage is attenuated by the rejector circuit, the 1088 kHz matching circuit and the output circuit of the 1088 kHz transmitter and

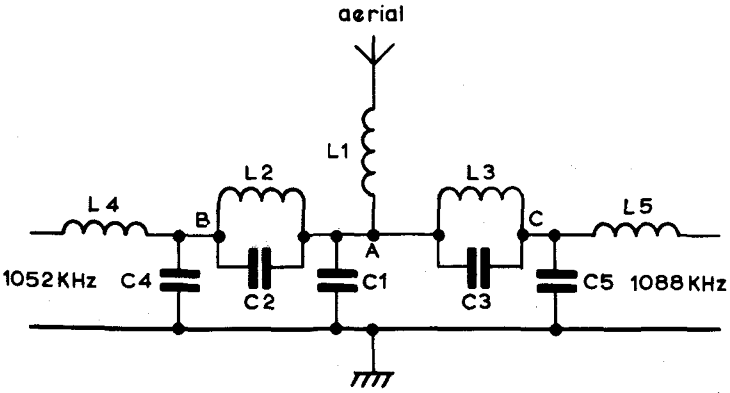

Fig. 7 - Combining circuit for 1052 and 1088 kHz

component values

L_1	8·5 μH	C_1	1320 $\mu\mu$F, 3·7 kV
L_2	17·6 μH	C_2	1220 $\mu\mu$F, 10 kV
L_3	18·1 μH	C_3	1260 $\mu\mu$F, 8·7 kV
L_4	133 μH	C_4	246 $\mu\mu$F, 8·8 kV
L_5	120 μH	C_5	108 $\mu\mu$F, 8·2 kV

Voltage ratings are peak values for two 1 kW transmitters simultaneously modulated 100%

computation shows that the unwanted voltage reaching the anode is 7·7 volts. The reactances of the output circuit components are required for this computation; values for 1088 kHz are given by the formulae in the footnote on page 2 and must be modified by the frequency ratio to obtain values for 1052 kHz. A similar computation shows that the unwanted voltage at the anode of the 1052 kHz transmitter is 7·5 volts.

Sideband Rejection. The amount by which the rejection at the sidebands falls below that at the carrier is calculated by assuming the unwanted transmitter to be detuned. Unwanted voltages for the ± 1 kHz sideband frequencies, calculated in this way, are given in Table 3.

TABLE 3

Unwanted Voltages at Sideband Frequencies

Frequency kHz	Voltage
1051	10·5
1053	11·2
1087	10·9
1089	10·4

These voltages are about 3 dB greater than the voltages at the carrier frequencies. The circuit therefore satisfies all the design requirements except that for pass loss, which is slightly exceeded at 1052 kHz.

Finally the voltage ratings of the capacitors are calculated as follows. The powers delivered to the aerial by the 1052 and 1088 kHz transmitters are 870 and 896 watts respectively. The impedances at A given in Table 2 enable the voltages at this point to be calculated; they are 606 and 717 volts at 1052 and 1088 kHz respectively. When both transmitters are modulated 100% the peak voltage at A is the sum of these voltages multiplied by $2\sqrt{2}$. Thus the voltage rating of C_1 is 3·7 kV.

The voltage across C_2 at 1088 kHz is almost the same as that across C_1 at this frequency, i.e. 717 volts. At 1052 kHz the current through the rejector is 1·58 amps and its impedance is 52 + j1765 ohms; thus the voltage across C_2 at this frequency is 2·80 kV. Addition as before gives the voltage rating of C_2 as 10 kV. The voltage rating of C_3 is 8·7 kV.

The voltage across C_4 at 1088 kHz is negligible. The impedance at B is 399 + j1930 at 1052 kHz and the current is 1·58 amps. Thus the voltage at B at 1052 kHz is 3·11 kV. The peak voltage across C_4, for 100% modulation, is therefore 8·8 kV. The voltage rating of C_5, calculated in the same way, is 8·2 kV.

A table of component values and voltage ratings is given below Fig. 7.

JMP

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey